Ensemble Assimilation of Doppler Radar Observations

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LONG-TERM GOALS

The final goal of this project is to provide the US Navy with an increased capability of using Doppler radar observations in the detection and prediction of hazardous weather events that usually have a strong randomness in nature and affect the Navy operations, especially over oceans and in remote areas. By developing a high-resolution data assimilation capability that can effectively assimilate Doppler radar observations along with other conventional and remotely-sensed data, the US Navy will have the ability to analyze and forecast the battlespace atmospheric conditions with sufficient detail and accuracy for supporting the Navy mission in threat detection, weapons deployment, and weather safe operations.

OBJECTIVES

The objective of the study is to develop an advanced ensemble-based radar data assimilation system for the US Navy and to address some critical scientific and technique issues associated with ensemble radar data assimilation. The radar data system that will be developed will use flow-dependent background error covariance (instead of the static background error covariance) to account for the complexity and rapid change in the dynamical and microphysical structures inside and outside storms. The system will assimilate all the observed variables from different types of sensors, including Doppler radars, satellites, UAVs, and conventional meteorological observations, simultaneously to allow full interactions among the assimilated variables during the data assimilation to keep the balances among the dynamics, thermodynamics and microphysics in the model initial fields. The system will be able to use the observations from many types of radars on different platforms (WSR-88D, DoD meteorological radars and tactical radars both on-land and shipboard, etc.) with an appropriate quality control. Multi-scale data assimilation capability will also be one of the major features of the new radar data assimilation system that allows observational data at different scales to be assimilated concurrently to ensure the scale balance in the ensemble analyses.

APPROACH

The ensemble Kalman filter (EnKF) recently developed at NRL will be the major tool for this study. All the radar data processing and quality control systems previously developed at NRL will be extended to cover the ensemble-based data assimilation and integrated into the EnKF for radar data

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decoding, pre-processing, quality control, bias removal, and observational error estimation. The proposed ensemble radar data assimilation system will assimilate the raw Doppler radial velocity observations directly in the observational space. This will help to reduce the errors induced during the pre-retrieval and interpolation of wind vectors. A data thinning algorithm will also be developed for radar observations to reduce the data density (especially near the radar locations) and hence the data dependency before assimilation. During the last two years, NRL, NSSL and OU have jointly developed a data thinning algorithm for Doppler radial velocity. This algorithm will be further refined and used in the proposed ensemble radar data assimilation system. The NRL 3D Radar Mosaic will serve as the reflectivity data thinning algorithm.

The forward radar observation operators previously developed at NRL for the 3d/3.5d-Var will be adapted for estimating the radar observations in observational space from ensemble forecasts. For storm-scale data assimilation, one of the biggest challenges is the missing storms in the background fields so that there are no estimated radar observations available at observation locations for the data assimilation. The use of ensemble forecasts as the background should have some advantages over the use of a single deterministic forecast in this aspect. But appropriate ensemble spread that covers all the uncertainties of the model forecasts is critical. An adaptive inflation algorithm previously developed for the EnKF will be refined for radar data to assure the appropriate ensemble spread in both the ensemble analyses and forecasts.

Localization is a necessary step in all ensemble-based data assimilation systems to account for the insufficient ensemble size due to the lack of computational power. The length scale of the localization is a very sensitive parameter that affects the ensemble analyses. The assimilation of storm-scale data along with the large- and synoptic-scale observations makes this challenging issue even much more complicated. In this study, we will develop an observation-adaptive, variable-dependent, multi-scale localization algorithm. This algorithm will use a multiple-localization procedure and determine the localization scale based on observational data type, the control variable, and the statistics of the observational and background errors.

Experiments of ensemble radar data assimilation with simulated and real observations will be conducted and the results will be compared with those from the 3d/3.5d-Var. This will help to investigate the impact of the flow-dependent background error covariance on analyses and forecasts. Furthermore, the comparisons between the variational and ensemble-based approaches will also be very useful in the development of a future hybrid radar data assimilation system.

WORK COMPLETED

During the fiscal year 2011, studies were conducted, as a continuous effort, to further advance NRL capability in acquisition, processing, and quality control of real-time radar observations of reflectivity and Doppler radial velocity from both the WSR-88D networks and SPS-48E shipboard radars. A new radar data quality control technique for ground and sea clutter was developed and successfully tested with archived SPS-48E/HWDDC data set from the USS PELELIU. The Radar Echo Classifier (REC) algorithms (both Fuzzy Logic 1 and 2 versions) originally developed by NCAR were improved. The Fuzzy Logic 1 version was converted to a MATLAB version at NRL. The improved versions were applied to SPS-48E radar observations and tested for both ground and sea clutter removal.

Major research and development efforts in the past year, however, were focused on the development of NRL ensemble radar data assimilation capability for the Navy's Coupled Ocean/Atmosphere

Mesoscale Prediction System (COAMPS®) to further enhance NRL capability and accuracy in the prediction of storms of all temporal and spatial scales. Several technical and scientific accomplishments have been achieved. Some of the cutting edge researches studies in radar data assimilation further improve our understanding of radar data impact on storm prediction. Following are the details of the new components we recently added to the NRL ensemble radar data assimilation system and the major scientific accomplishments we achieved in our recent study with the system:

1) Algorithms and software were developed to integrate Doppler radar observations, after quality control and super-obs, into NRL Atmospheric Variational Data Assimilation System (NAVDAS) innovation vector files. By adding forward operators for both Doppler radial velocity and reflectivity to NAVDAS, the background fields of these parameters are also computed from COAMPS forecasts of three-dimensional winds (u, v, w) and microphysical fields. This work provides the observational radar data input to the EnKF for assimilation into COAMPS. Meanwhile, it also makes the radar data available to other NRL data assimilation systems (the 3D-Var and the 4D-Var) and paves the way for assimilating radar observations into any of these variational data assimilation systems as well as a potential hybrid data assimilation system in the future. These algorithms and software have been extensively tested.

2) Forward observation operator was also developed for Doppler radial velocity for COAMPS EnKF that converts the forecasts of 3D winds (u, v, w) from each member of the COAMPS ensemble in model grid space to ensemble estimation of Doppler radial velocity in observational space.

3) A multi-scale localization algorithm for radar observations has been developed and tested for the EnKF. It contains storm information from synoptic scale to convective scale. Its impacts on background error covariance and hence storm forecasts at different scales have been examined.

4) Flow-dependent cross-variable background error correlations between the observed Doppler radial velocity (Vr) and the model state variables of temperature (T), horizontal winds (u, v), and water vapor mixing ratio (q_v) were computed from COAMPS ensemble using the EnKF and fully examined regarding localization length scale and ensemble size.

5) Case studies were conducted to test the ensemble radar data assimilation system. Observations of Doppler radial velocity from WSR-88D radars in Eastern US were assimilated into COAMPS with the EnKF concurrently with conventional and non-conventional observations from RAOB, surface stations, buoys, commercial aircrafts, and satellites. Impacts of ensemble radar observations on the prediction of storms at different scales were fully examined. Quantitative verifications of the ensemble forecasts against RAOB observations were performed that showed improvement in the forecasts of model state variables at both large- and convective scales by radar observations.

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RESULTS

1. Radar data quality control

1.1. Improvement and testing of NCAR REC with SPS-48 data

Dr. David Pan worked under an ONR Summer Faculty Fellowship with Dr. Harasti to improve the NCAR REC with a Fuzzy Logic 2 upgrade. Dr. Pan developed a MATLAB version of the original NCAR REC Fuzzy Logic 1 version in a more flexible framework that will allow training the software with Fuzzy Logic 2 statistical parameters. The goal is to hopefully gain improvements in performance to the original REC, and make REC less radar-type dependent by explicitly including the radar-type dependencies of the parameters in the spread of the REC membership functions; i.e. Fuzzy Logic 2 permits the inclusion of the spread. Dr. Pan's tests on the above mentioned USS PELELIU data set and several WSR-88D challenging cases revealed the following. For WSR-88D data, the original REC performs well on AP ground clutter but poorly on coastal sea clutter. As mentioned above, for SPS-48E/HWDDC data, the original REC had notable difficulty at identifying clutter and if also incorrectly removed a significant fraction of precipitation echo. Figure 1 gives an example from the test of the MATLAB version of the NCAR REC Fuzzy Logic 1 with SPS-48E radar reflectivity observations. While most sea clutter was removed, the ground clutter of Hawaii Islands still remains in the image (Fig. 1b) after the quality control.

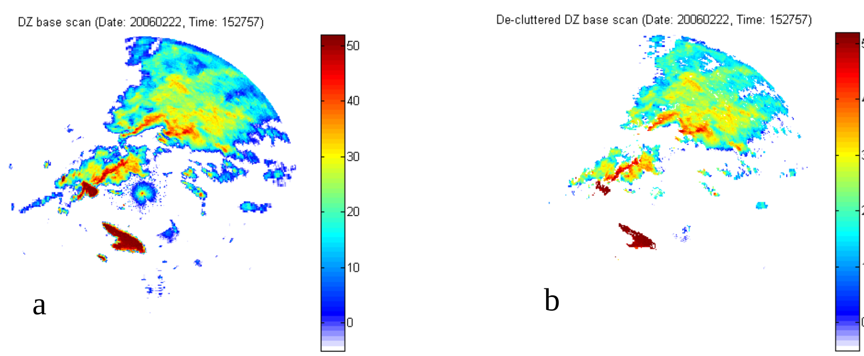

Figure 1. Radar reflectivity (dBZ) from SPS-48E/HWDDC aboard USS PELELIU before (a) and after (b) application of NCAR REC Fuzzy Logic 1 (MATLAB version developed at NRL). Some sea clutter is removed. However, the ground clutter of Hawaii Islands is still seen after the quality control.

1.2 Development of NRL ground and sea clutter removal

A new radar data quality control technique for ground and sea clutter was developed by Dr Paul Harasti. A novel equation for the vertical gradient of reflectivity (VGR) was developed and threshold calibrated to identify ground and sea clutter using an archived SPS-48E/HWDDC data set from the USS PELELIU. Unlike previous VGR estimates developed by other investigators, the new estimate is normalized by the radar range to account for the vertical spreading of the radar beam, and a refractivity-curvature-corrected estimate of the altitude differential is utilized in the calculations.

Preliminary tests of the method on the archived data set indicate that this new single-parameter (VGR) method out performs other methods applied to the same data set. These methods were the NCAR Radar Echo Classifier (REC) and the method of Steiner and Smith (2002) which both require multi-parameter input in addition to a less accurate estimate of the VGR. Figure 2 shows an example from recent test of the newly developed algorithm with SPS-48E archived data. As you can see by comparing the results in Fig.2 with those in Fig. 1, the new algorithm was significantly more effective than the NCAR REC in correctly identifying both clutter and precipitation. Similar comparison testing is planned for WSR-88D data.

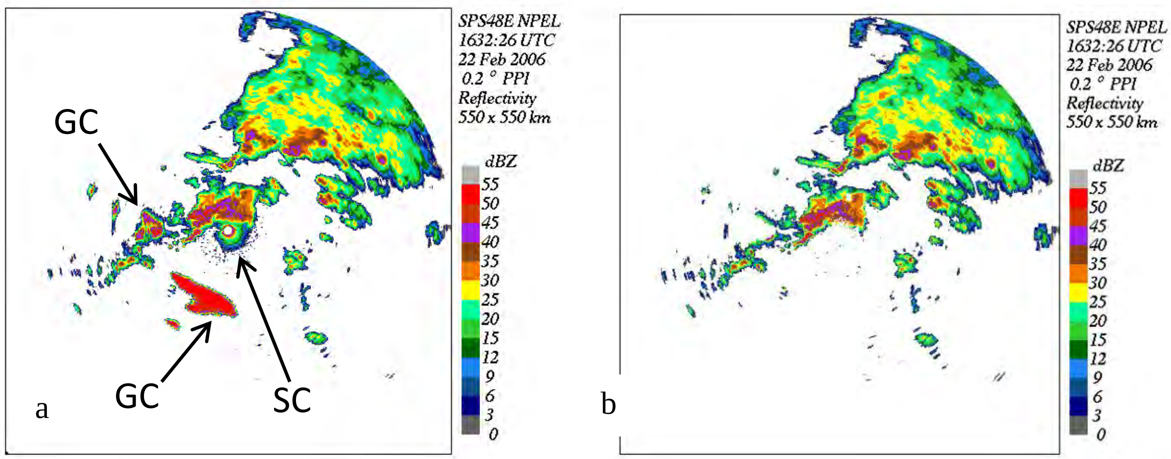

Figure 2. Radar reflectivity (dBZ) from SPS-48E/HWDDC aboard USS PELELIU before (a) and after (b) application of NRL ground and sea clutter removal. Most ground and sea clutter is removed by the data quality control algorithm.

2. Ensemble radar data assimilation

2.1. Flow-dependent background error correlations between Doppler radial velocity and model state variables

In the assimilation of Doppler radial velocity (V_r), four model state variables are updated. They are T, u, v, and q_v. Background error correlations between the observed V_r and the state variables are computed dynamically for each radar observation. This is done in two steps. First, ensemble estimations of Doppler velocity, V_r^m, at observation locations are computed from COAMPS ensemble forecasts of (u, v, w) for each member with the EnKF equipped with the forward operator for V_r . Then, correlations between V_r^m at the observation location and each of the ensemble state variables of T, u, v, and q_v at model grid points are computed. Figure 3 gives examples of the computed flow-dependent correlations of V_r to u, V_r to v, V_r to T, and V_r to q_v, respectively, for an observation of V_r at the location indicated by the dot. Thirty-two members of COAMPS ensemble were used for this calculation. The symbol R in Fig. 3 indicates the radar location. Negative correlations of V_r to u and V_r to v are correct for this particular location of V_r with respect to the radar location. Large correlations of V_r to u and V_r to v are found basically for almost all V_r observations. However, Fig. 3 shows relative small correlations of V_r to T and V_r to q_v. It should be pointed out that this is just for this particular observation location. We found that most V_r observations in the same study have notable correlations to T and to q_v.

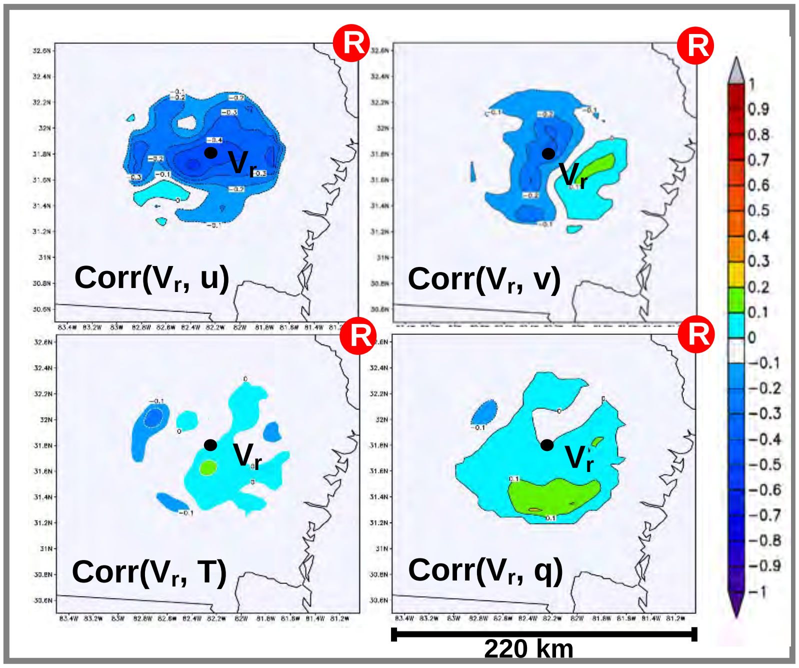

Figure 3. Background error correlations for a Vr observation (the dot) estimated from COAMPS ensemble forecasts (5-km resolution and 32 members) using the EnKF. The R indicates location of the Doppler radar.

2.2. Impact of localization length scale on background error correlations

One of the big challenges for radar data assimilation is the length scale used to specify the background error covariance and correlations. Most previous studies in radar data assimilation use length scale of $10^0 \sim 10^1$ km in specifying the background error covariance and correlations based on the consideration that radars mainly observe fine structures inside storms. This is true for single radar observations. For a well-designed radar network (such as the WSR-88D network in US), however, storm structures from large scale to convective scale should be well observed by radars on the network and contained in the observational data. To re-present these storm structures in the model initial fields, these radar observational data should be assimilate into the model using multiple length scales in defining background error covariance and correlations. In this study, a multi-scale localization algorithm was developed for the EnKF to assimilate radar observations from the WSR-88D network.

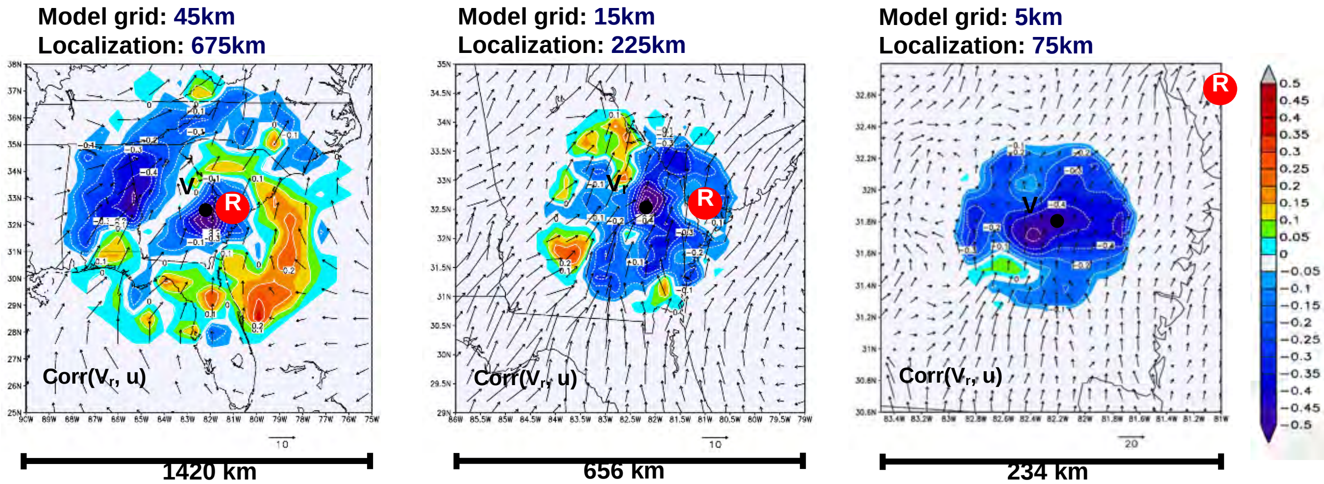

Figure 4. Background error correlation (colored areas) between Vr and u for the same Vr observation shown in Fig.1 estimated from COAMPS ensemble forecasts with 32 members using the EnKF. Three different localization length scales of 75 km, 225 km, and 675 km were used. The horizontal winds (the arrows) are on the same level as the observed Vr. The R indicates the location of the Doppler radar.

Figure 4 shows examples of estimated background error correlations of V_r to u for the same V_r observation shown in Fig. 3 from the EnKF with a multi-scale localization algorithm. The length scales used in Fig. 4 are 75 km, 225 km, and 625 km, respectively. Obviously, all three correlation fields show patterns following the background horizontal winds on the same level, which is dynamically meaningful. If look closely, however, we find that the correlation from the 75-km localization is basically the central part of the larger correlation field estimated from the 225-km localization, which again looks similar to the central part of the even larger correlation field generated by the 625-km localization. This suggests that localization algorithm works, as it is designed for, to reduce or eliminate spurious correlations between the observation and the grid points far away from the observation location without significantly affecting the correlation pattern inside the localization. The correlation pattern from the 75-km localization is relatively simple with the maximum value close to the observation location. Noises start appearing around the correlation field from the 225-km localization. The correlation from the 625-km localization shows complicated structures with multiple correlation bands and maxima. Studies are underway to investigate whether the correlation bands on each side of the center band are spurious or real. This study will help to ascertain whether or not large scale localization can be used for radar observational data assimilation.

2.3. Improvement in storm prediction at both convective- and large-scales

To test the ensemble radar data assimilation system and to examine the ensemble assimilation of radar observations on storm prediction, a storm case in June 2005 along the east coast of US was selected. Figure 5 presents a picture of the storm system from GOES-12 satellite at 1145 UTC 28 June 2005. As you can see, the storm covered basically the whole US east coast stretching from the Gulf of Mexico all the way to New England. In the southern part of the storm, many strong convective storms due to the large amount of available moisture were embedded inside the large storm system. This is an appropriate storm case for studying multi-scale radar data assimilation.

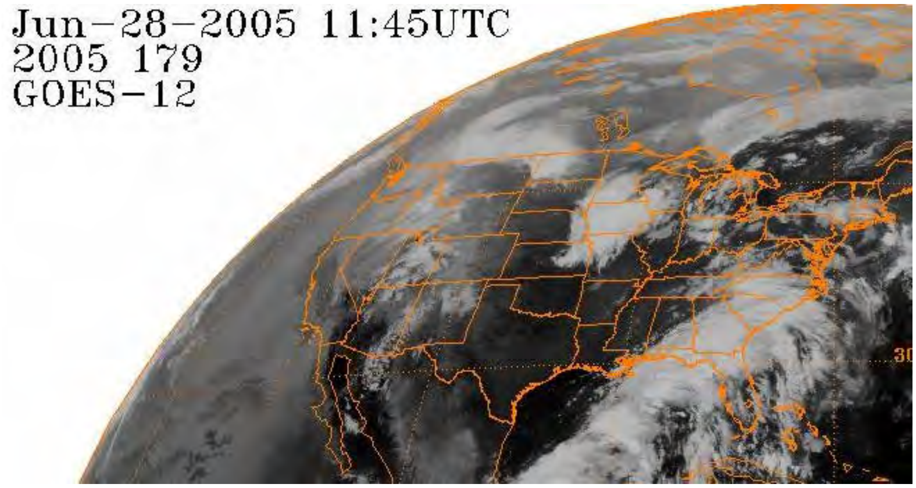

Figure 5. GOES-12 satellite IR image of the storm system along the Eastern Coast of US on June 28, 2005.

Observations of Doppler radial velocity from the level-II (volume scans) data of twenty-two WSR-88D radars in the storm region were collected and assimilated, after quality control and super-obing, into the COAMPS three-nested grids along with all other conventional and satellite observations available at 1200 UTC 28 June 2005 with the EnKF. Figure 6 shows the COAMPS domains of the three nested grids and the locations and data coverage of the twenty-two WSR-88D radars. Thirty-two members of COAMPS ensemble were used for this case study. For comparison, the current operational NAVDAS 3D-Var was run to assimilate exactly the same observations except radar measurements into COAMPS with the same model configuration. Figures 7a and 7b give 9-hour forecasts radar composite reflectivity for the area of Florida and Gulf of Mexico from the inner domain (5-km) of COAMPS runs initialized by the EnKF with radar V_r assimilation (EnKF-RW) and by the NAVDAS 3D-Var without radar data assimilation (NAV-3DVAR), respectively. Figure 7c presents the observed radar composite reflectivity for verification. Improvement in storm forecasts along the east coast of South Carolina, Georgia, and Florida and in the area of Florida Panhandle and Gulf of Mexico are very evident, demonstrating the positive impact of ensemble radar data assimilation on convective storm prediction.

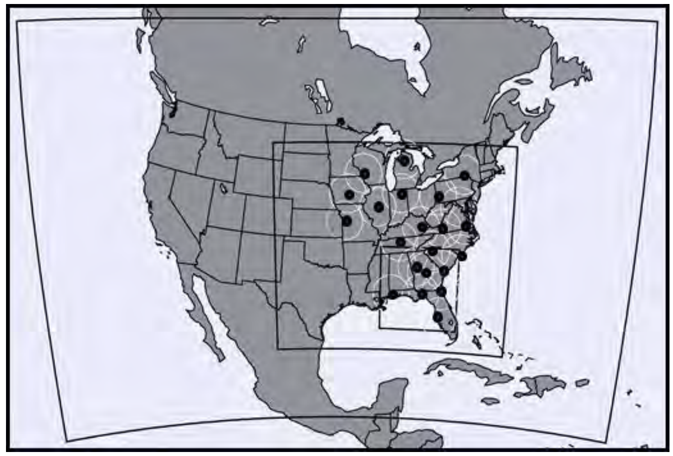

Figure 6. Domains for the three COAMPS nested grids (with grid resolutions of 45 km, 15 km and 5 km, respectively) and the locations (the dots) and the data covered areas (the white circles, at 150-km data cut off) of 22 WSR-88D radars from which the radar observations of Vr are collected and assimilated for this study.

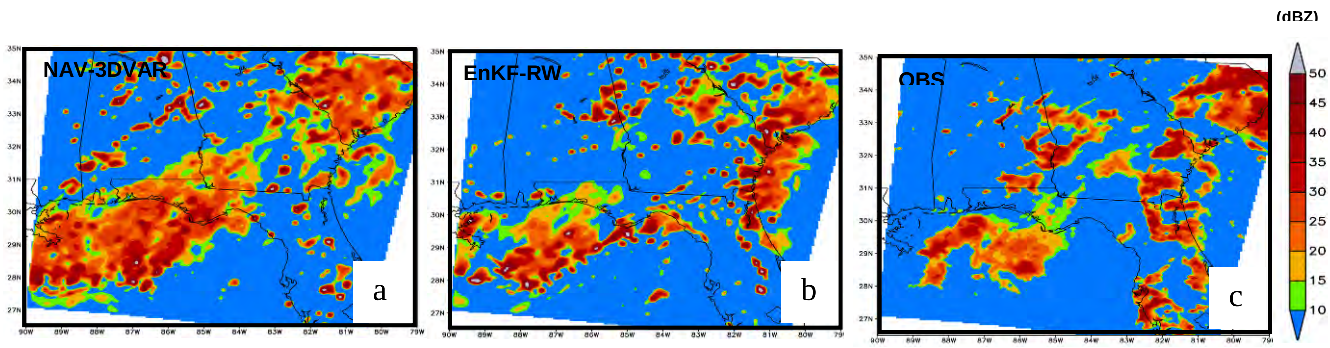

Figure 7. 9-hour forecasts of radar composite reflectivity (dBZ) from NAV-3DVAR (a) and EnKF-RW (b). (c) is the radar composite reflectivity valid at 2100 UTC 28 June 2005 observed by several WSR-88D radars in the storm area.

To further investigate and quantify the impact of ensemble radar data assimilation on storm prediction, COAMPS forecasts of T, u, v, and q_v from EnKF-RW and NAV-3DVAR are verified against RAOB observations. Figure 8 gives the calculated root-mean-square (RMS) errors over the outer domain (45-km) and the inner domain (5-km) from the two experiments as a function of forecast hours. Apparently, EnKF-RW out performs the NAV-3DVAR for all the forecasts of temperature, winds, and water vapor over both the large and small domains during the whole forecast period of 72 hours. It should also be pointed out that all the forecast improvements by EnKF-WR in Fig. 8 are statistically significant. Figure 8 further demonstrates the potential of ensemble radar data assimilation in improving storm forecasts not only at convective scale but also at synoptic scale.

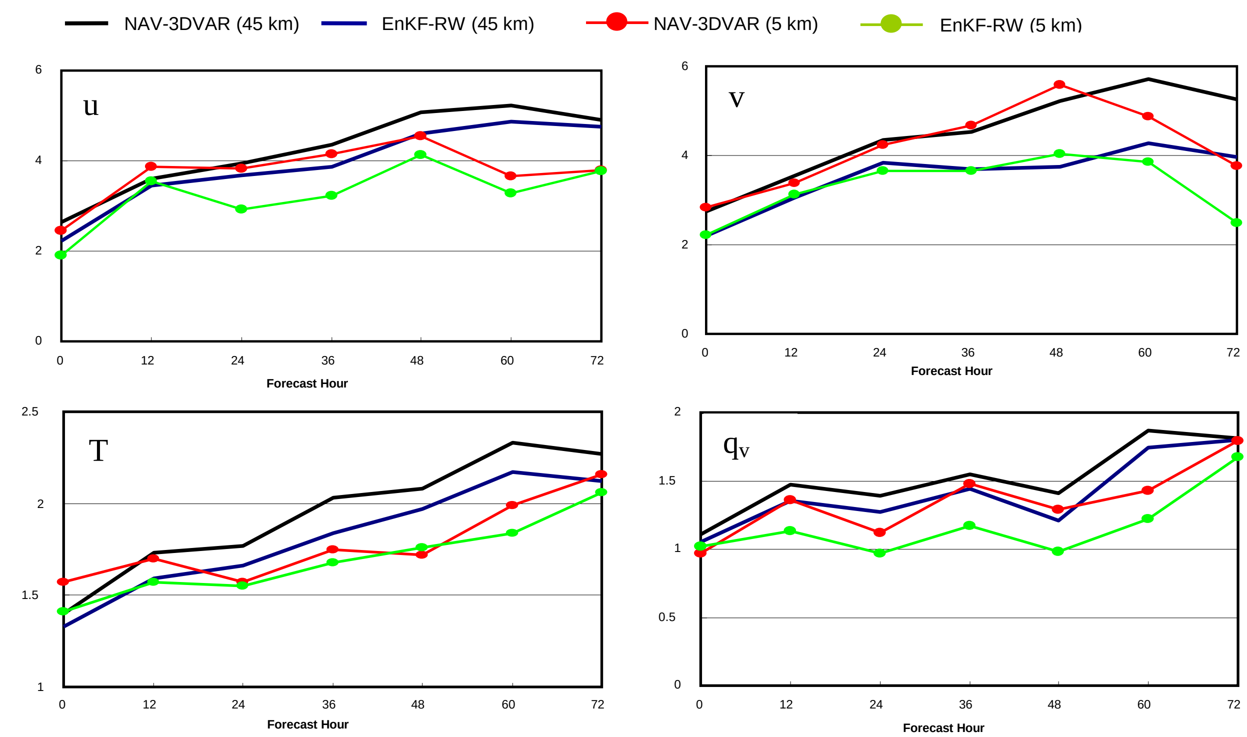

Figure 8. Root-mean-square (RMS) errors of u (ms^{-1}), v(ms^{-1}), T (degree), and q_v (gkg^{-1}) from NAV-3DVAR and EnKF-RW verified against RAOB observations as a function of forecast hours for both COAMPS 45-km and 5-km grids.

IMPACT/APPLICATIONS

Real-time applications and several transitions have been made from the efforts of developing NRL radar data processing, quality control and assimilation capabilities. The NRL Doppler Radar Data Processing and Quality Control System is now mature systems for processing real-time radar observations from both S-band and C-band Doppler radars, including the DoD meteorological and tactical radars (such as the land-based Supplemental Weather Radars, or SWR, and shipboard SPS-48E and SPY-1) and those in the WSR-88D Network, with various data formats. These systems also supported the NRL Nowcasting Demo at the Naval Strike and Air Warfare Center (NSAWC) at Fallon, Nevada for providing real-time analyses and nowcasting of weather conditions for Navy pilot training. The Lossless Differential Compression of Weather Doppler Radar Technique significantly compresses the shipboard SPS-48E and SPY-1 Doppler radar UF format data files to ensure the real-time transfer of the full-volume, full-resolution radar observations from ships with limited bandwidth to the Fleet Numerical Meteorology and Oceanography Center (FNMOC) for data assimilation. The software has been transitioned to the Hazardous Weather Detection and Display Capability (HWDDC) and is being installed to the SPS-48E radar systems onboard twelve U.S. Navy aircraft carriers and amphibious assault ships. The newly developed ensemble radar data assimilation system will provide the US Navy with new capabilities of concurrent multi-sensor, multi-scale assimilation of all measurements of the battlespace environment available from conventional and non-conventional meteorological and tactical networks, including those from Doppler radars, into COAMPS with the utilization of multi-scale, flow-dependent background error covariance that accounts for the complex and rapid changes in storm structures.

TRANSITIONS

None for FY11.

RELATED PROJECTS

Related NRL base projects include the 6.2 task BE-435-047, Advanced Assimilation of Non-conventional Data for Improved High-Impact Weather Prediction. Other related projects include Radar Data Quality Control and Assimilation At the National Weather Radar Testbed (NWRT**)**, 6.4 Reach-Back Doppler Radar Data Assimilation (PMW-120, X2341) and 6.4 On-Scene Tactical Atmospheric Forecast Capability (PMW-120, X2342).

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